# High-efficiency solar cells for large-scale electricity generation & Design considerations for the related optics

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Optics for Energy

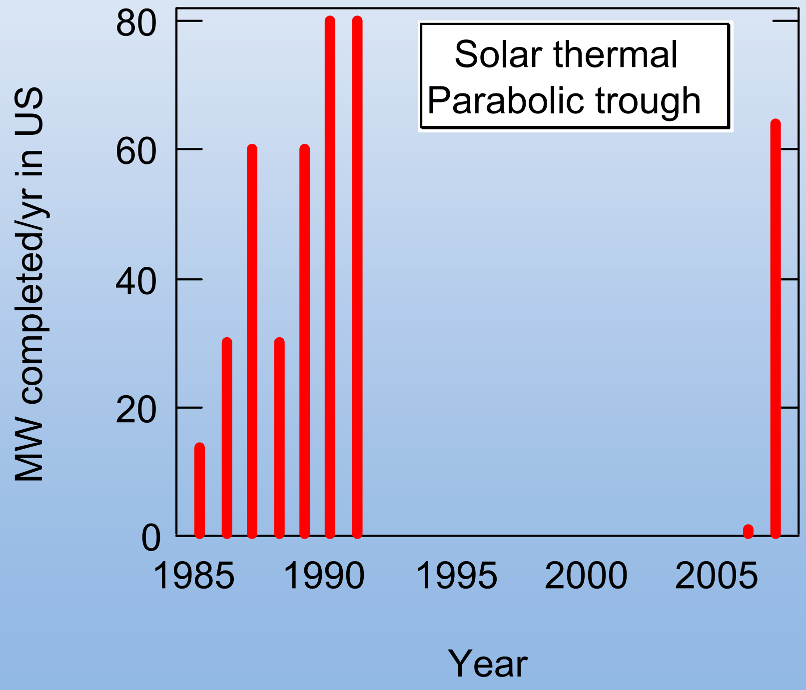
Frontiers in Optics (FiO) 2007 – 91st OSA Annual Meeting

# Outline

- Solar is growing very fast
- Optical concentration
  - Reduces semiconductor material
  - Increases cell efficiency
- The physics of solar cells and high efficiency
  - Why using multiple junctions increases efficiency
  - Success of GaInP/Ga(In)As/Ge cell -- 40.7%
- Optics - design considerations
  - Overview
  - Solar thermal electricity generation
  - PV - high concentration 500X - 1000X (high efficiency)
  - PV - low concentration 2X-4X (Si)

# Solar thermal electric

- Parabolic trough is the primary technology today
- Resurgence of interest
- ~ 400 MW installed
- Currently generates ~ 0.01% of US electricity
- Economical for > 100 MW in sunny areas



64 MW Solargenix Parabolic Trough Plant in Nevada - 2007

1-MW Arizona Trough Plant – near Tucson, AZ - 2006


SAN BERNARDINO COUNTY
CALL
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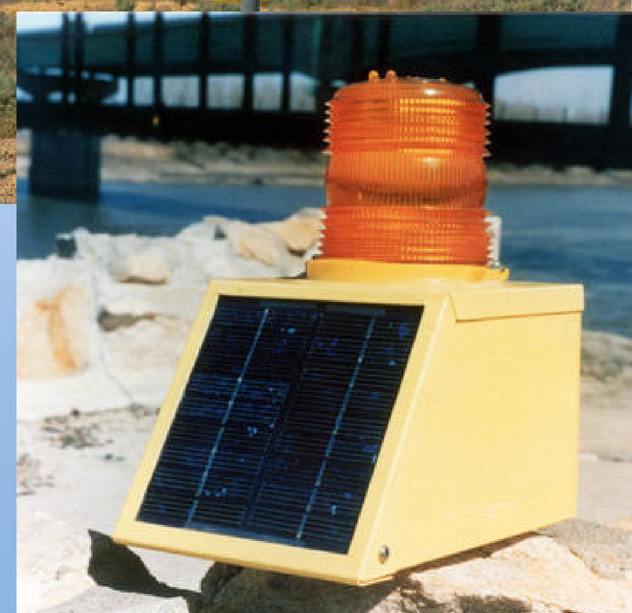
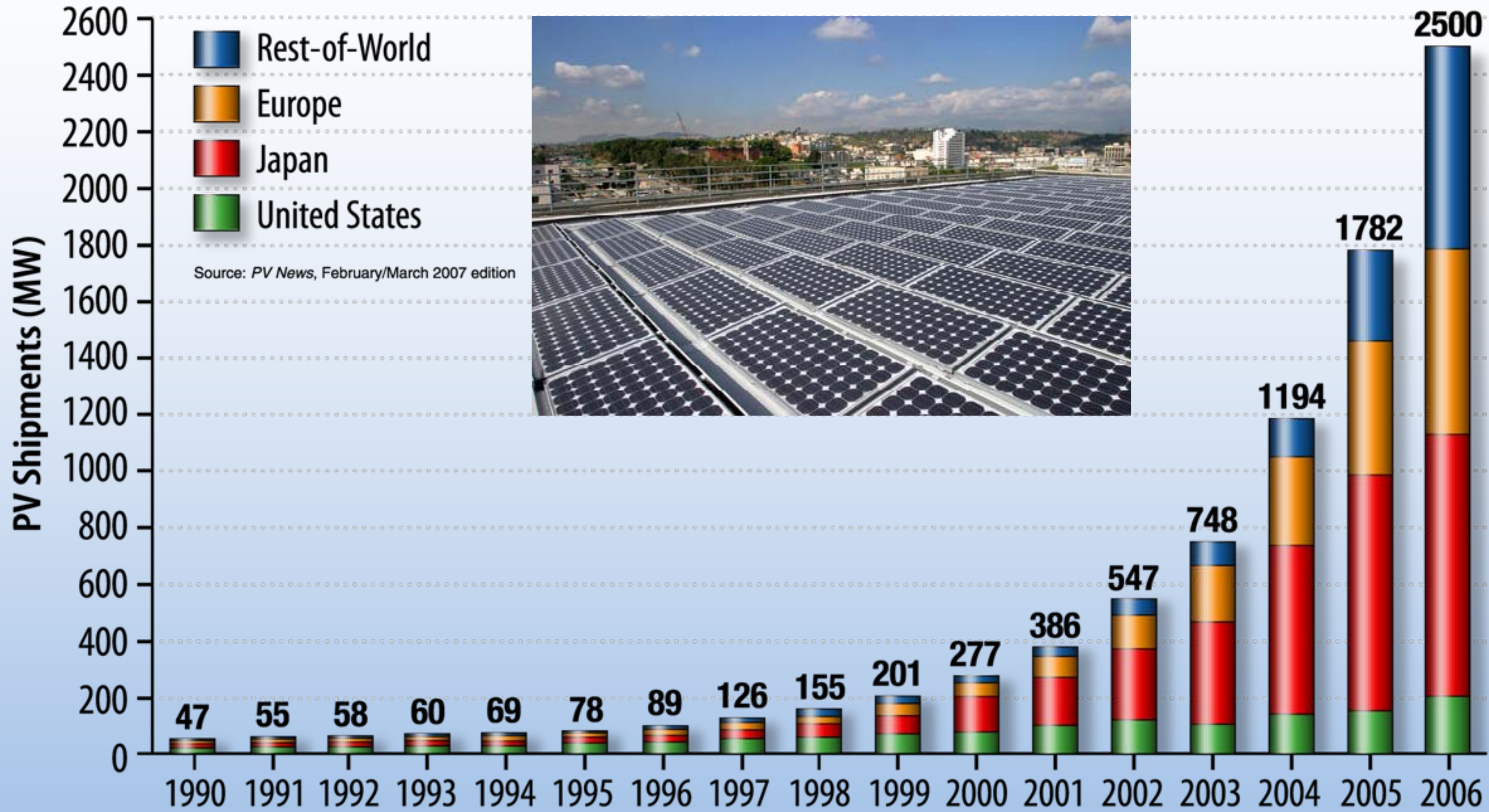



MARYLAND
SOLAR
DECATHLON

# Growth of photovoltaic industry

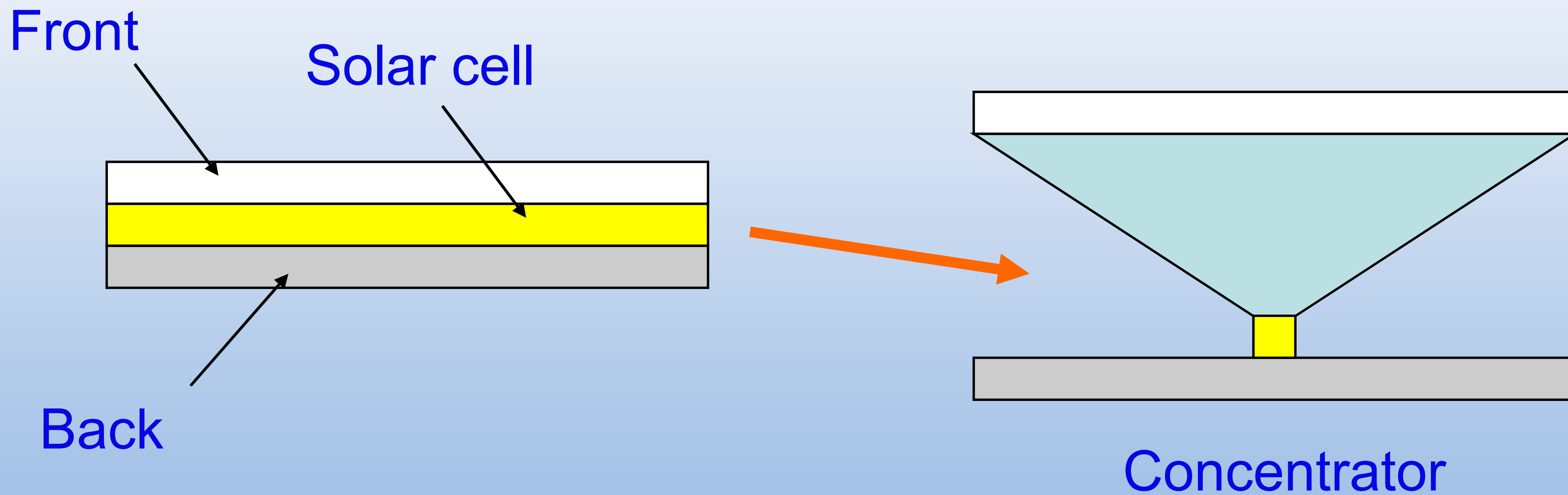



*0.06% of electricity now comes from solar - extrapolates to > 5% in 2020*

*competitive with conventional electricity for 0.1% - 1% of market; more in future*

Rogol, PHOTON International August 2007, p 112.

# Industry growth is currently constrained by Si availability
# Reduce semiconductor material by concentrating the light




Concentration:

1. Reduces semiconductor use
2. Allows use of higher efficiency cell (higher system efficiency)

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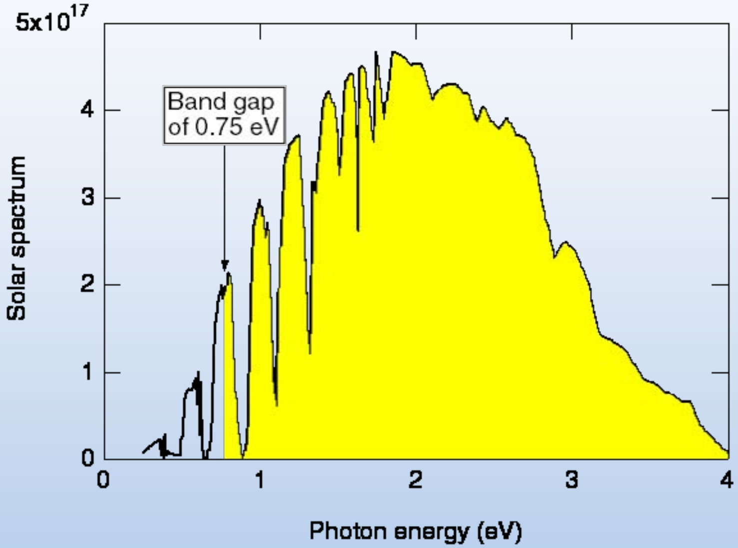
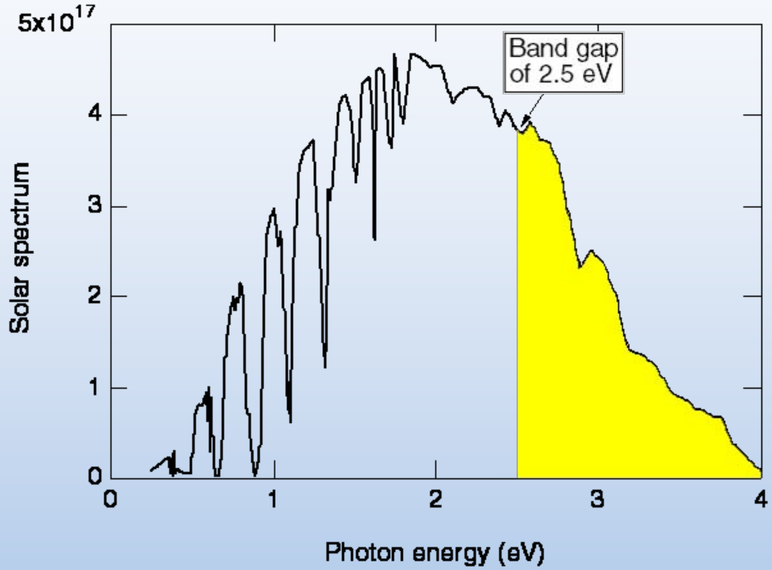
- Optics - design considerations
  - Thermal
  - PV - high concentration
  - PV - low concentration

# Optics in solar cells - getting the light into the active layers

- Broad-band anti-reflection coatings
- Light trapping (textured surface on front or back for Si)
- Many different approaches will be covered in other talks

# Why multijunction?
# Power = Current X Voltage



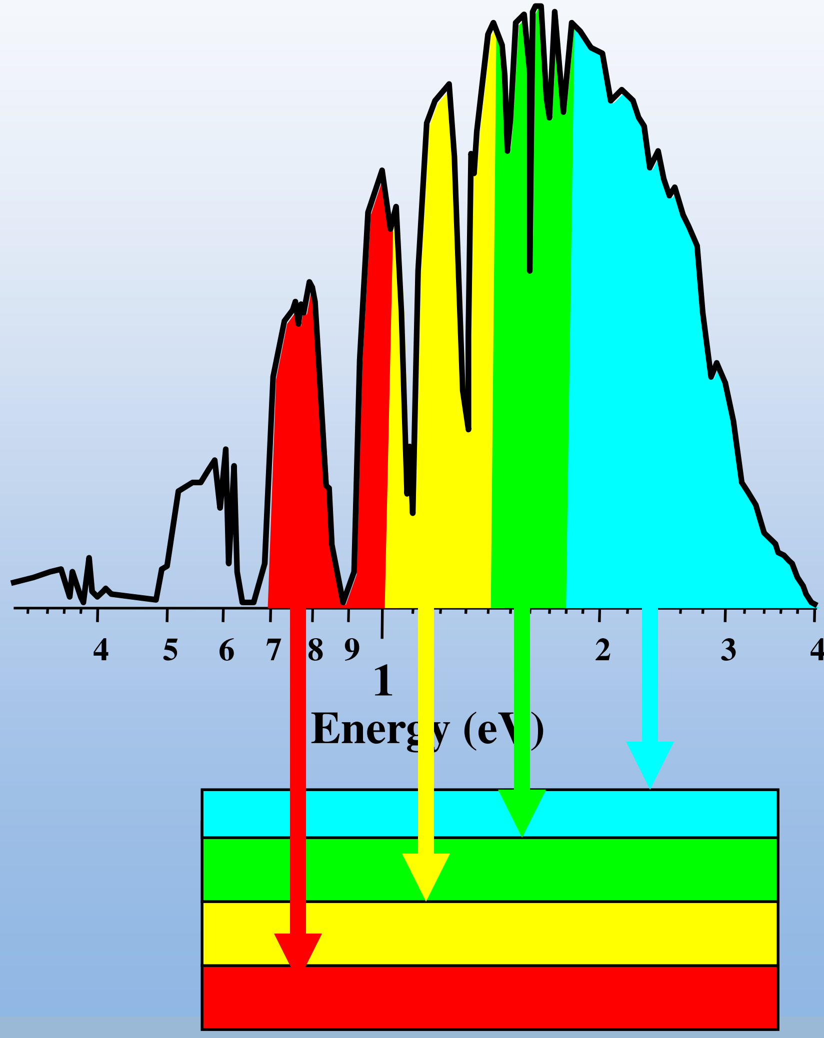




High current,
but low voltage
Excess energy lost to heat

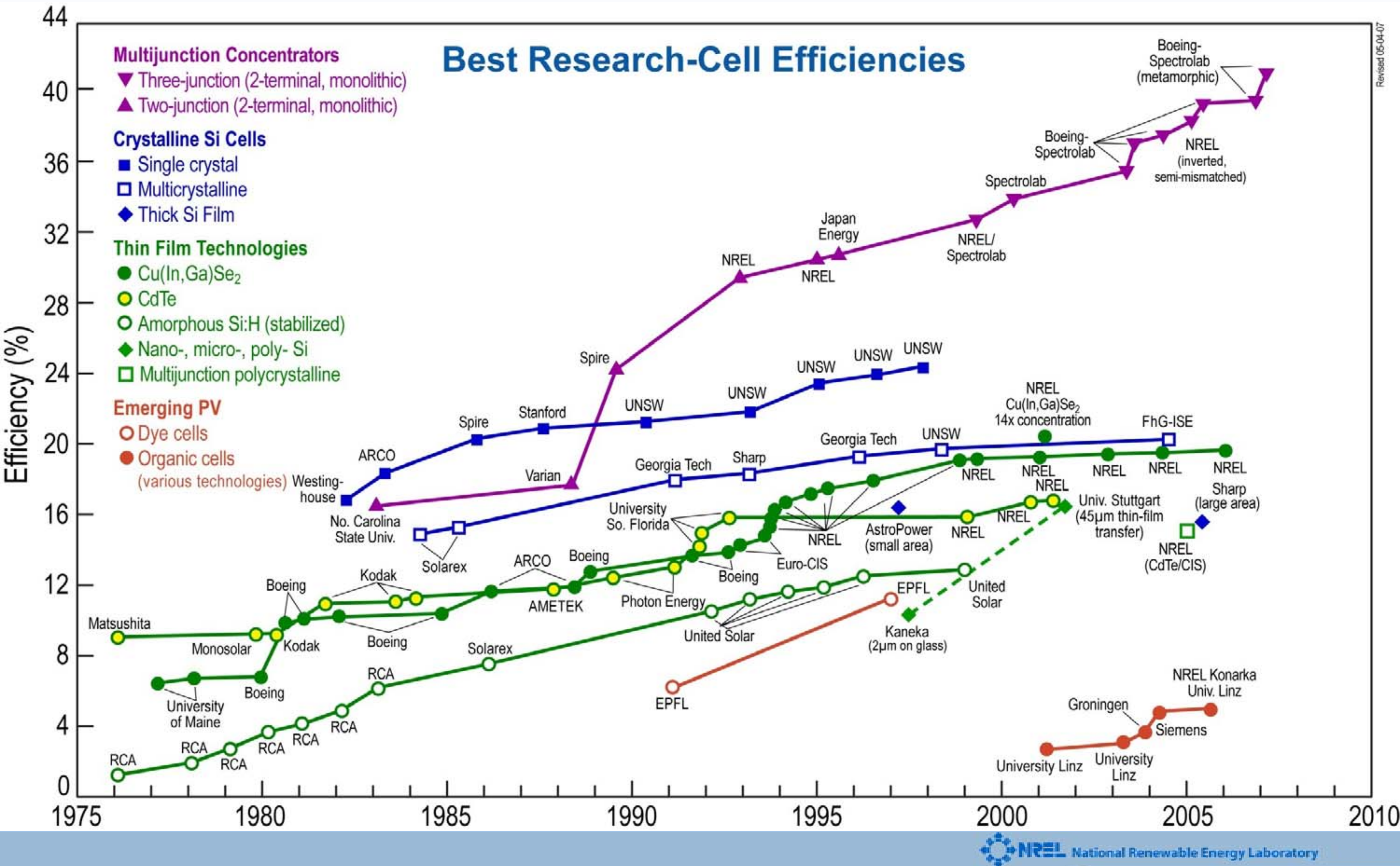
High voltage,
but low current
Subbandgap light is lost

*Highest efficiency: Absorb each color of light with a material that has a band gap equal to the photon energy*

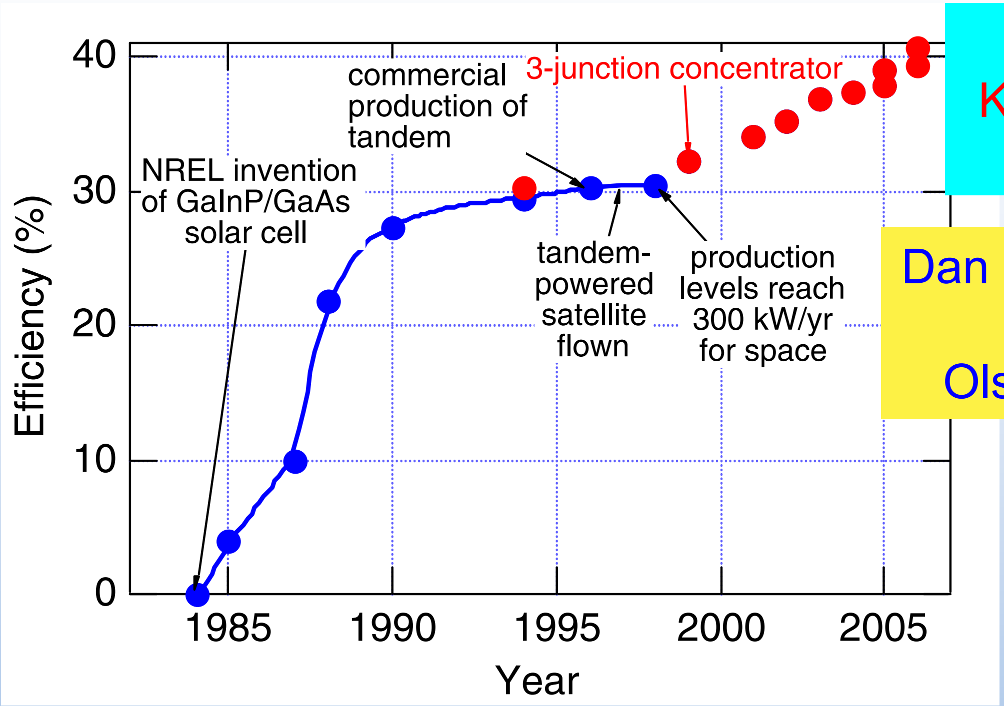
# Multijunction cells use multiple materials to match the solar spectrum



# Champion solar-cell efficiencies



# Success of GaInP/GaAs/Ge cell



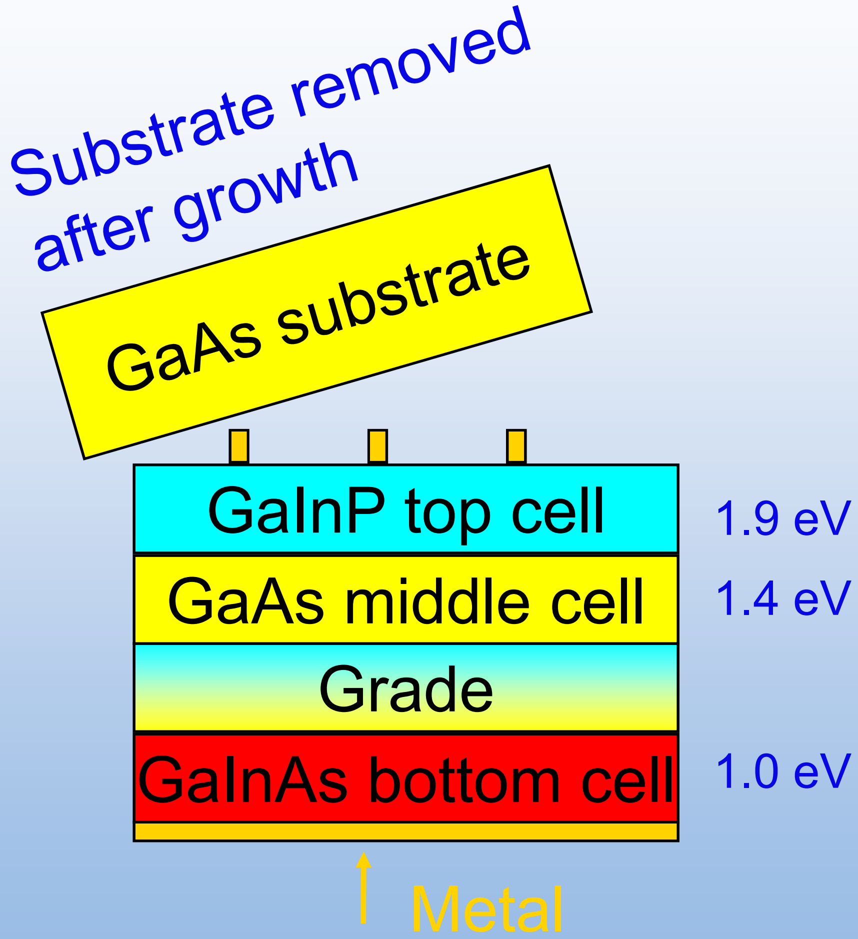

40.7%
King, APL
2007

Dan David Prize
2007
Olson, Kurtz

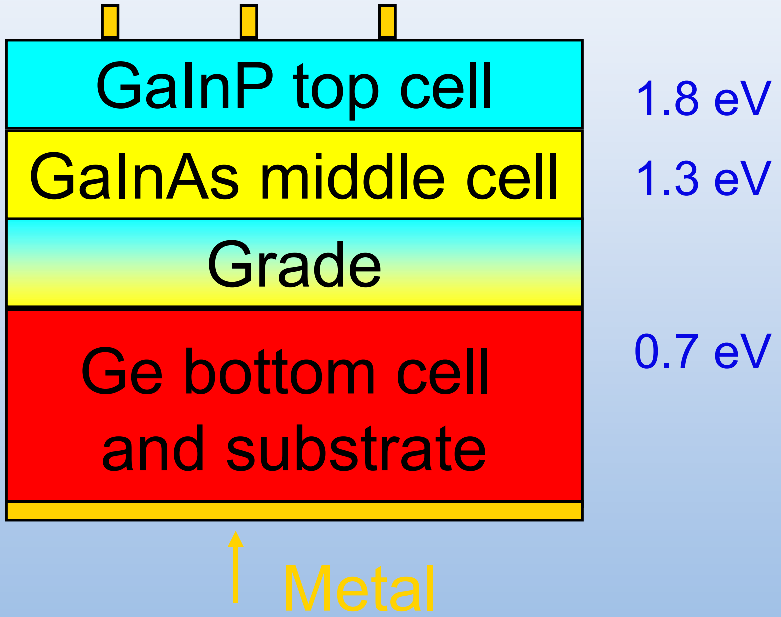
Mars Rover powered by multijunction cells

*This very successful space cell is currently being engineered into systems for terrestrial use*

# High-efficiency mismatched cells




38.9% @ 80 suns
Geisz, 2007




40.7% King, 2006

*New research: from 40% to 50%*

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  - PV - high concentration (low T, uniformity)
  - PV - low concentration (high acceptance angle, reliability)

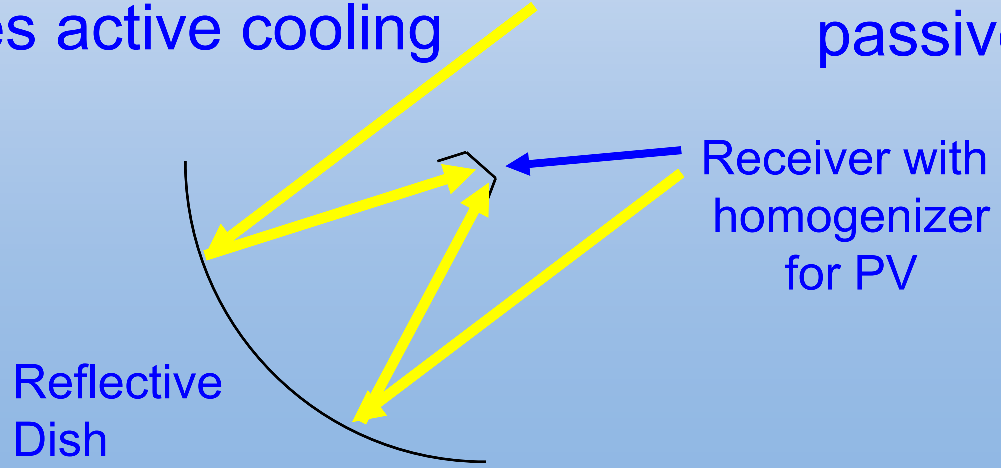
# Key issues for optical design

- Low cost
- High efficiency over broad spectral range
- Large acceptance angle for easy alignment and use of diffuse radiation
- Soiling (maintenance)

# Reflective optical designs

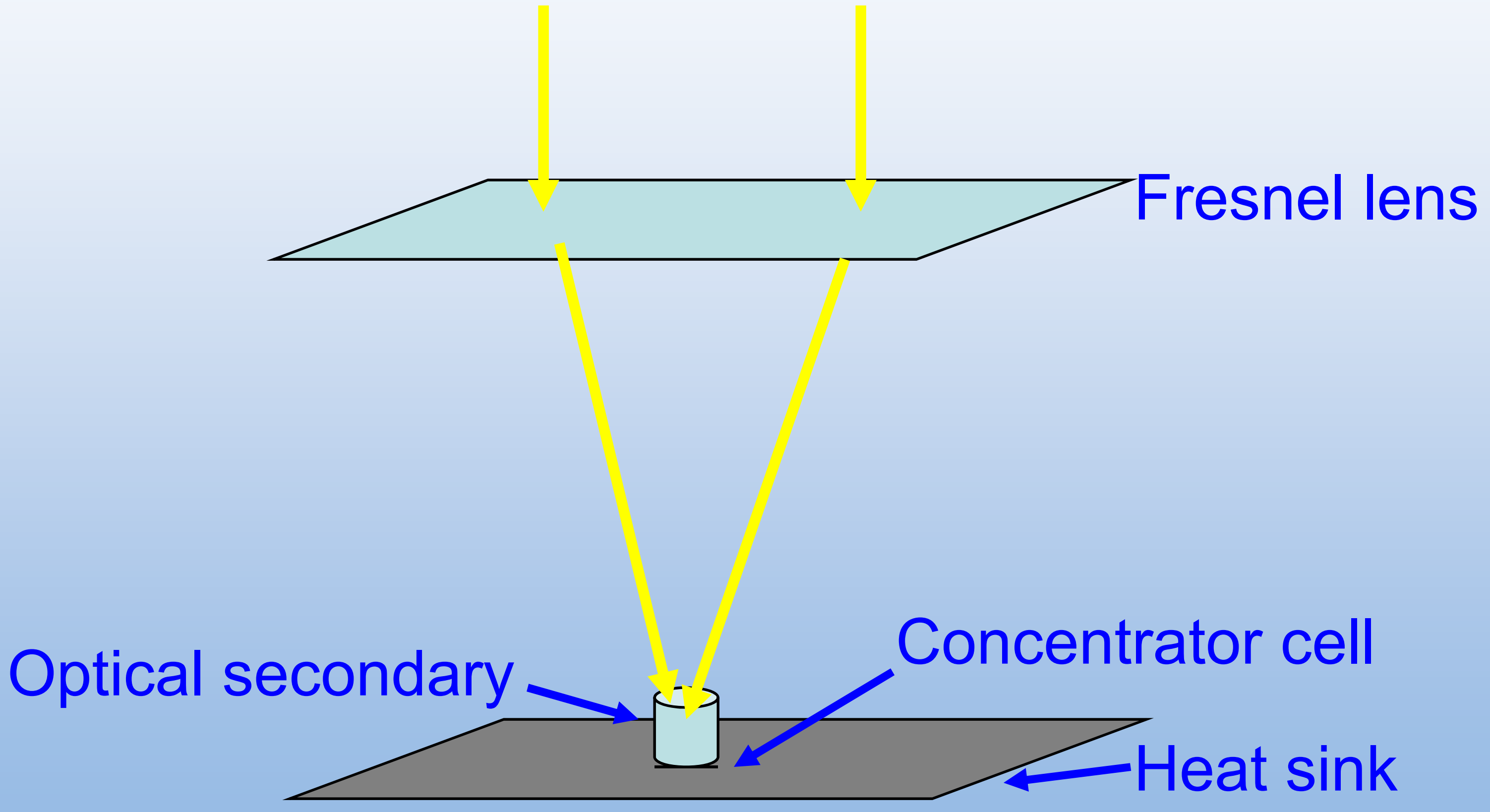
Large dish: Stirling engine; PV requires active cooling

Microdishes can be passively cooled



# Reflective optical designs - troughs

# Refractive designs for PV - large Fresnel

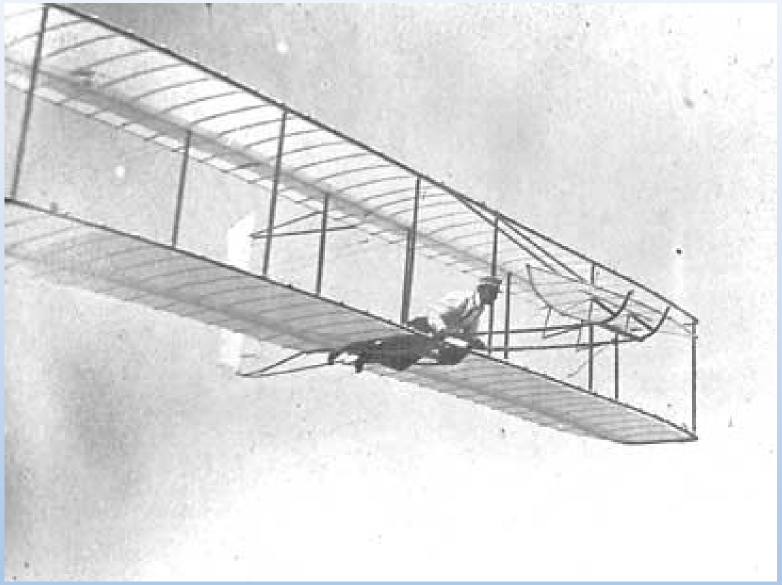


# Refractive optical designs

Fresnel lenses focus light on small cells
Passive cooling

Small lenses and small cells can lead to thin designs and "flat-plate" cooling

# What will concentrators look like in the future?



Could we have predicted 100 years ago what airplanes look like today?

*Innovation*

# Optics for solar thermal

- Solar thermal
  - Trough - convenient transport of working fluid
  - Dish or tower - higher temperatures
- Guidelines
  - Hit the target
  - Energy is all that counts

# Uses for optics for solar

- Concentrating PV
  - High concentration enables use of high-efficiency cells
  - Any concentration reduces use of semiconductor material
- Guidelines differ for PV
  - Keep temperature low (lose 0.2-0.4%/° C)
  - Uniformity concerns
  - Chromatic aberrations
  - Don’t care about lowest E light; blue is important

# Series connection of cells requires uniformity of light for CPV

100 W can be derived from
1 V @ 100 A
or
100 V @ 1 A

High voltage is always preferred, so connect cells in series

Series-connected cells: current is limited by cell with least light;

*Need same light hitting each cell*

*Uniformity of light is important for CPV, not thermal*

# Uniformity challenge for CPV

- Dish - need uniform image
- Trough - need clean image (pay attention to shadows for supports and end of image)
- Fresnel - make each cell and lens identical

# Low-concentration

Reduce Si usage with low concentration

- Theoretically for non-imaging optics: $C_{max} = n/\sin\theta$
- For point focus 4 X, limit is acceptance angle ~ 45°
- Tracking is now used in many systems
- Efficiency of optics is important
- Use design that is unaffected by soiling
- Small cells may allow for very thin systems with minimal cooling problems
- Historically, low-concentration systems have shown new degradation mechanisms

# Summary

- Photovoltaic industry is doubling every two years
- Using concentration may help the solar industry grow even faster
- Multijunction cells provide the path to high efficiency; > 40% and are still increasing
- The optical designs are varied and the requirements differ for solar thermal and PV

# Flying high with high efficiency

Cells from Mars rover may soon provide electricity on earth

*High efficiency, low cost, ideal for large systems*